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Instant Numerical Simulation Research on Fire Ventilation in Extra-long Highway Tunnel in Zhongnanshan Section of Qinlin Mountains

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Abstract

Using the secondary exploited pre-manage software of FDS build up the arc physical model of the extra-long highway tunnel. Confirm the size of the fire according to the condition in the tunnel. Choosing FDS simulate the ventilation in Zhongnanshan extra-long highway tunnel, and get the characteristics of smoke affluent. By considering the smoke affluent surface arrive different cross sections at different time, obtain the level spread speed of the smoke affluent in the tunnel. Then considering the tunnel security analysis partition the tunnel to up-fire zone and down-fire zone, and build up the safety standard of vehicle and personnel life. Combining the results of the simulation, obtain the conclusion that the vehicle and personnel life is safe in the tunnel under the condition of fire.

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Keywords: ventilation under condition of fire; extra-long highway tunnel; instant numerical simulation; FDS; analysis of security

1. The Current Severe Fire Situations

The Qinlin Zhongnanshan extra-long highway tunnel is situated on Xi'an City – ankang highway. It is the longest road tunnel in Asia and the second in the world. This is 18.2 km long and operates one direction in two tube tunnel. The importance of the operation in Zhongnanshan extra-long highway tunnel is the fire prevention and rescue which bring to highly concern.

Computer numerical simulation has simulated accurately, convenient, save cost and other advantages. In China, the Computer numerical simulation of the fire prevention and rescue in extra-long highway tunnel are limited by the computing power. Many use the stable state model to make the research. The result showed after the fire develops the stable state, smoke characteristic state variable descript fire's static description [1][2]. But the actual fire is a continual dynamic process, smoke characteristic parameter along with time change, but momentarily changes. The fire rescues are very important in different period's smoke characteristic changes to the highway tunnel fire prevention.

This article uses the three dimensional numerical simulation method to carry on the unsteady state simulation of the fire pattern under highway tunnel's velocity field, the temperature field to reveal different time fire smoke stream pattern. To set up the fire control, the personnel escape and the vehicles dispersal to provide the reference.

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2. Numerical model

2.1. Choose the computation model

This simulation use fire dynamics simulator software FDS (version 4) calculate the situation of fire and smoke spread. The Fire Dynamics Simulator is a product of the construction and the fire research lab development in the National Institute of Standards and Technology (NIST) of the United States. Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) model of fire-driven fluid flow. It may simulate the air speed, the temperature and the smoke mobility status of the three-dimensional space , the FDS software further information has in the NIST related report states [3][4] in detail.

But the FDS software defines the rectangular structure only; it is quite difficult to define the tunnel's circular arc structure. This simulation uses the Sichuan fire prevention research institute to carry on the re-development based on the FDS software to process the software before irregular structure definition; it is a very good solution to solute tunnel structure definition problem [5].

2.2. Calculate the object physical model

The simulation selects the section of 775m in the Shanxi Qinling Zhongnanshan extra-long highway tunnel to take the appraisal object, the cross section area of the tunnel structure are shown in Figure 1. Suppose the fire point is located at tunnel road surface and outside 25m. The simulation model and computation grid are shown in Figure 2.

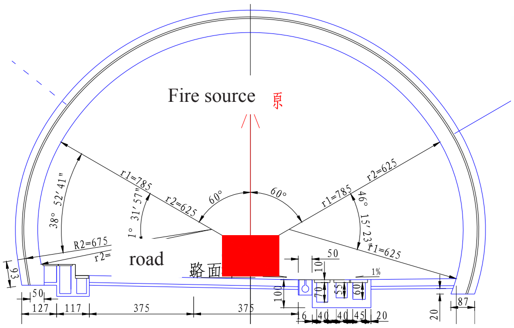


Fig. 1 Sectional view of Tunnel

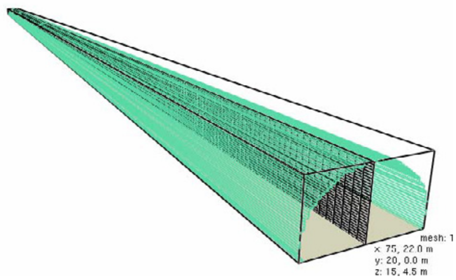


Fig. 2 Geometry of FDS simulation

3. Determinate the Computation operating mode

3.1. Determinate the fire scale in tunnel

To determinate the fire scale, the consideration factor are many and the majority are non-quantifying. So forecasts or set up fire scale accurately and comprehensively is not easy. Through to various countries highway tunnel fire's investigation and study, forbids or limits the oil truck and it is loaded with the explosive, dangerous and flammable material vehicles through the tunnel. Fire scale's determination takes the object by the passenger vehicle and the large-scale cargo vehicle, generally divides into the following three kind of fire scale:

Table 1. Thermal release power of fire scale in tunnel

Fire scale	Operation management of dangerous vehicle	Fire in number of cars(car)	Vehicles type	Gas quantity(L)	Thermal release power（MW）
Small fire	forbids or limits	1	Passenger vehicle	60	3
Medium fire	forbids or limits	1	cargo vehicle	150	20
Large fire	forbids or limits	2	cargo vehicle	300	500

Our country present code to stipulate when fire happen, the discharging fume wind speed are design to 2-3m/s. it is according to the common tunnel fire of the 20MW thermal control to get the discharge fume wind speed value [6][7]. Generally speaking, the fire prevention ventilates of tunnel should be a medium fire (20MW), the main cause are aimed at the large-scale fire to establish the tunnel firefighting equipment, causes the tunnel construction cost high. And the large-scale fire occurs is not often.

Therefore, uses the medium fire scale in the simulation process (20MW), the fire hazard area uses recommendation value of PIARC,1987 (Permanent International Association of Road Congress）: 2mx6m.

3.2. Determinate the wind speed in fire area upstream

In the tunnel fire and smoke backflow control's research, "The critical speed" indicates that the smallest ventilates speed to eliminate smoke backflow phenomenon. When flows to the fire hazard, the ventilated wind speed equal to or large than the critical speed, the backflow phenomenon will not happen. The smoke stream can force to the downstream. At present the critical speed value has taken the tunnel ventilation system design main standard [8].The aim of the ventilation design in the Qinling Zhongnanshan extra-long highway tunnel's is using the ventilation system to control the flow of smoke, when the fire happen in the tunnel. To stop the backflow's production, removes the smoke, provides the secret channel and the convenience for the personnel dispersal and the fire rescue, guaranteed that the personnel's safety on vehicles in the fire area upstream. Therefore, the artificial draft air current must use to be higher than the critical wind speed in tunnel.

Use the Kennedy critical wind speed and Atkinson method to find out the critical wind speed. The critical wind speeds are 2.35m/s and 2.43m/s [9] respectively. In this simulation, the wind speed of the upstream in fire area is 3.0m/s.

3.3. Determinate the simulation time

Considered when fire in the tunnel, achieves the stable stage may be 2~10min. The simulation time is 900s.

4. The safety standard of the people in vehicles

In the related tunnel the safe evacuation and the smoke control may supply the choice of the solution to an inspection standard, according to fire when the upstream and downstream different characteristic, its criterion is as follows:

4.1. Fire upstream

When the fire occurrence in tunnel, vehicles in the tunnel fire point up stream's which will stop going forward, the people approaches the fire point , they get out the car and exit from a recent person line of horizontal channel to disperse to the non-fire tunnel. The distance between person lines of horizontal channel is 250m, so the dispersal distance is longer. The normal speed of the people in the tunnel to evacuate is 1.5m/s, but in the case of smoke may be only 1.0m/s. Therefore, the people to evacuate in upstream fire area required longer time. Firefighters arrived and started the fire work, also need a secure environment. The security criterion of the ignition point in upstream fire area is not polluted by the spread of smoke.

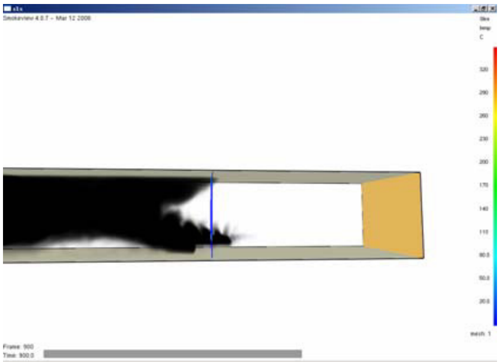
4.2. Fire downstream

When the fire occurrence in tunnel and under the longitudinal ventilated function, the smoke toward the tunnel fire point downstream spread. Vehicles in the fire point down stream's continues to go forward, until disperses leaves the tunnel. Therefore the fire point downstream security time must be the available safe escape time (ASET) is bigger than required safe escape time (RSET) which is the vehicles disperse time. The fire spread's speed should not larger than the vehicles speed. For safety, when the haze spread at the tunnel downstream, it is in the unsafe condition. It will harm the safety of the people in vehicles.

5. Analyze the flow of smoke

5.1. Analyze the wind speed in fire area upstream

In the figure 3, the fire achieves the stable stage in 900s. The smoke density and wind vector are known in the figure 4. When the wind speed in the fire area upstream is 3m/s, there has a backflow in the fire point and tunnel central crown. Above the fire, a big vortex is formed, but the length of the backflow is very short. It has not surpassed the scope of the fire to arrive at the tunnel ventilation upstream, the smoke cannot spread to the tunnel fire point upstream.



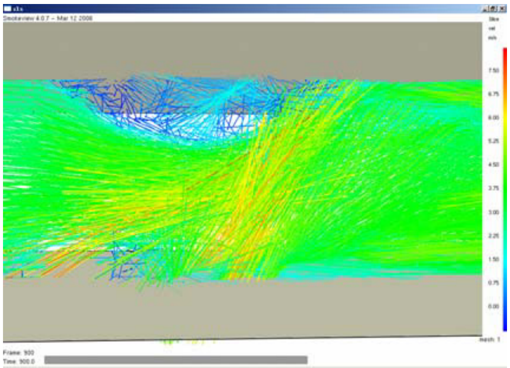
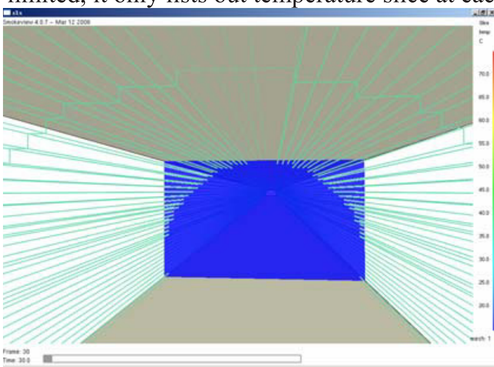


Fig. 3 Soot density at 900s Fig. 4 Vector plot at 900s

5.2. Analyze smoke and temperature in tunnel

In order to find out the temperature changes under the fire operating mode in the tunnel, in the numerical simulation process get the temperature slice in the following spot at 30s, 300s, 600s, the 900s. There are the lateral section of fire area, fire area downstream in 250m, 500m and 750m place tunnel and tunnel central lengthwise section. As space is limited, it only lists out temperature slice at each time in fire downstream 250m as figure 5~8.



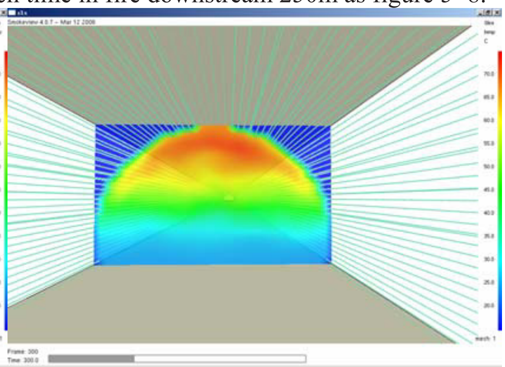
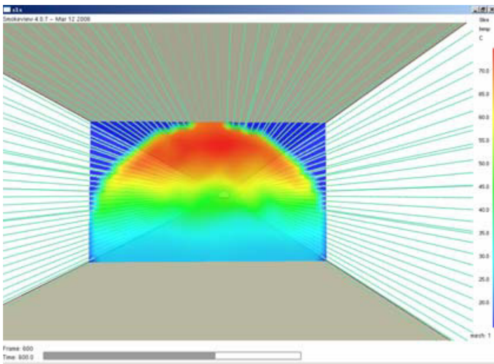


Fig. 5 Temperature contour at 250m downstream at 30s Fig. 6 Temperature contour at 250m downstream at 300s



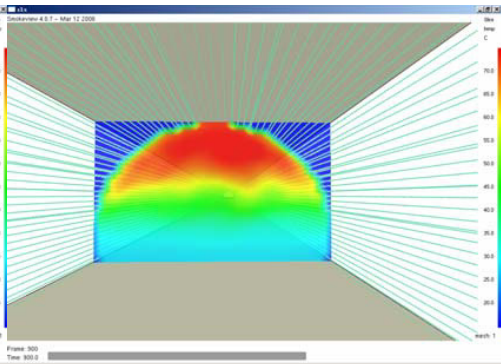


Fig. 7 Temperature contour at 250m downstream at 600s Fig. 8 Temperature contour at 250m downstream at 900s

Looking from the simulation result, the maximum temperature of the smoke in fire area reaches 1020℃. But above the fire area, the upstream loose influence and the temperature is low. When the simulation is finished (900s), the maximum temperature of the smoke away from the ground 2m place is 110℃. In the 30s , to compare the fire downstream 250m, 500m and the 750m place temperature and the initial time temperature. It have not changed and proved that smoke didn`t invade and attack. Increases along with the time, the smoke temperature of different sections' increase gradually, the smoke temperature of various sections' will tend to be stable after 600s. Contrasts the temperature in each section with same time, the temperature which is near the fire area is higher. The smoke in the downward spread process is mixing the air in the tunnel and carries on the heat convection with the periphery tunnel wall. The temperature decrease gradually, the temperature is lowest located at the 750m place, and the temperature in the simulation terminal time (900s) is 45℃.

5.3. Analyze the velocity of the smoke spread

In the stable state simulation, the speed of the smoke spread indicated directly by the velocity vector chart that is expresses the dynamic smoke stream change with the static solution. The smoke in the spatial fluidity and the time continuous nature has not displayed, the situation of the smoke spread in the fire initial period cannot unfold. Providing the dynamic instruction for the vehicles person to escapes.

This time uses the unsteady state of simulate method. It can demonstrate smoke spreads in the tunnel process in the time and the space.

According to the distance between the time and the section of the fire smoke frontal area arrives at each tunnel lateral section to calculate each section of tunnel's average wind velocity, namely:

$$v=L/\Delta\tau \tag{1}$$

Inside the formula：

v—— the average of smoke spread speed in tunnel section (m/s)；

L—— the length of the tunnel section(m)

$\Delta\tau$—— the time of smoke spreads in the tunnel section(s)

Table 2 Spread of hot smoke gases inside the tunnel

Tunnel Section No.	Length of Tunnel Section(m)	Time taken for the smoke descend to level(s)	Time taken for the smoke spreads in the tunnel section(s)	Average of smoke spread speed in tunnel section(m/s)
1	250	43	43	5.81
2	250	95	51	4.81
3	250	150	55	4.54

In the above result, the smoke spread speed in tunnel quicker than in building (general 0.3m/s~0.8m/s).In the analysis of the smoke temperature, when the tunnel downstream is nearer to the fire area, the smoke temperature is higher. As a result of the air being heated and expansive action, the tunnel section leaves the fire point to be nearer; the spread speed of smoke is quicker. Otherwise, when the tunnel downstream is farther to the fire point, the smoke spread speed assumes gradually the reducing trend. Therefore people in vehicles to escape in the fire initial period and near the fire point is a key to all people in vehicles in the tunnel to escapes.

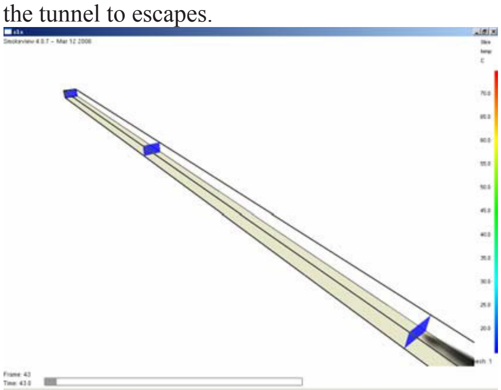


Fig. 9 Spread of smoke reaches at 250m downstream at 43s

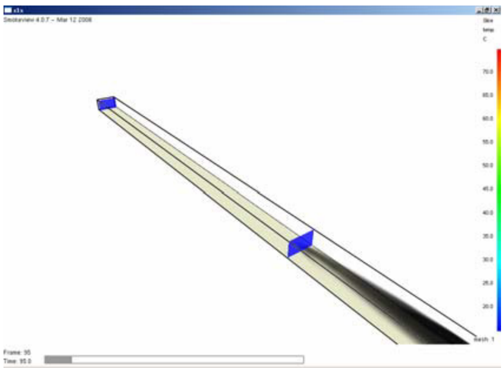


Fig. 10 Spread of smoke reaches at 500m downstream at 95s

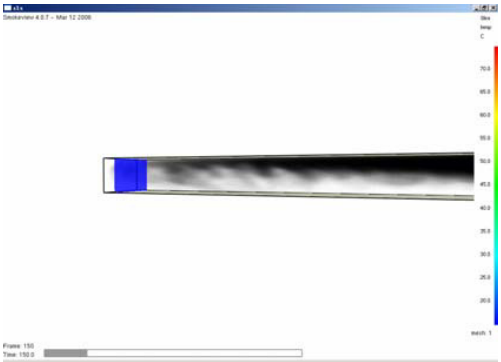


Fig. 11 Spread of smoke reaches at 750 m downstream at 150s

6. Analyze the safety of tunnel

6.1. Fire upstream section

Form the result of the smoke simulation, the 3 m / s wind speed of ventilation in upstream fire area are better to suppress the smoke outside the fire area to return to the upstream ventilation of the tunnel. The fire area upstream has not polluted by the smoke. It is better for the safety of evacuation. Also it is better for the Firefighters to put out the fire.

6.2. Fire downstream section

The design speed of the one-way traffic of vehicles in tunnel is 80 km / h which are equal to 22 m / s. it is greater than the average wind speed of the tunnel. It means that the vehicles speed inside the downstream fire area of the tunnel is faster than the speed of the spread of smoke. Have a greater safety margin; the people in vehicles can escape safety before the smoke is spread to.

7. Conclusion

In the light of the less research of the long highway tunnel in china, means more use of steady-state analysis of the simulation methods which have limitations. The numerical simulation research of the Qinling Mountains in the Zhongnanshan-long tunnel use the non-steady-state simulation method, the use of the secondary development of software for fire FDS, it simulate a section of the tunnel ventilation condition of the fire to determine the Fire heat release power, the laws of the flue gas flow, to combine the characteristics of people evacuated the vehicles in the tunnel and analyze the tunnel's safety. Concluded as follows:

(1)The use of non-steady-state simulation to describe the dynamic flow of gas inside the tunnel. From the perspective of movement to look at the process of development and change of the fire, to overcome the steady-state simulation analysis can only describe the static fire in a stable phase of the flowing characteristics, it does not reflect the shortcomings of the process of development and changes of the fire. This is a comprehensive study of the development of the fire mechanism in tunnel is a very important. From the development of philosophy, it is more scientific and rational.

(2)According to the characteristics of the fire prevention and rescue in highway tunnel, people evacuated and escape the vehicle in tunnel divided into the upstream of the fire area and downstream of the fire area were considered in two parts: The upstream of the fire area through a ventilation speed of the wind to control the backflow of the smoke. To ensure the environment of upstream tunnel can meet the safety of evacuation vehicles and fire extinguishing work requirements; vehicles speed inside the downstream fire area of the tunnel is faster than the speed of the spread of smoke, the vehicles can escape safety before the smoke is spread to.

(3)The ventilation wind speed of upstream of the fire area is 3.0m/s.The ventilation wind speed is higher than the Kennedy critical wind speed, Atkinson critical wind speed. At the top of the fire and the top of the tunnel are still have a large scroll, there are a short backflow. But it will not endanger the safety of people to evacuate vehicles and advantages to the fireman to put out the fire. Also, the ventilation wind speed of the upstream in fire area can meet the requirements of fire prevention and relief.

(4)Nearby the fire centre, the temperature is very high. But it affected by the ventilation airflow in the upstream fire area, the temperature of the nearby tunnel structure are greater reduce. The changes in temperature of the downstream fire area in tunnel are: in the fire early, the temperature of the downstream fire area is not change immediately. But there is a time lag; the length of the time lag is concerned the distance from the source of the fire. When the distance is father, the time lag is longer. With the further development of the fire, the temperature of the cross-section of the tunnel is gradually increased. After 600 s, it tends to stable. When section of the distance from the fire source is shorter, temperature is higher. On the contrary, temperature is lower.

(5)Use of non-steady-state simulation of dynamic continuity. According to fire smoke arrival at the every cross-section of the tunnel, the time and the distance between cross-section of the tunnel sections can calculate the smoke standard rate of spread is 4.5 ~ 6.0 m / s. Smoke spread speed is about the distance from the source of the fire. The distance is closer; the spread of smoke is faster. Also, it is a greater threat to the people in vehicles. In the initial stages of the fire, the most unsafe are the people in vehicles which near the accident points, the stage is the most critical period of the people in vehicles to evacuate and escape.

(6)Upstream fire area in tunnel didn`t affect by the backflow of smoke. It can maintain a safety evacuate environment. About the downstream fire area, it is a one-way traffic tunnels. The design speed is larger than the smoke spread speed in every section of the tunnel. Before the smoke is arrived, the people in vehicles in the downstream fire area can evacuate and escape safety. Integrate the situation of the upstream and downstream fire area, the ventilation guarantee the safety of people in vehicles to evacuate and escape in the fire happen tunnel.

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